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# CIRCUIT, METHOD AND SYSTEM FOR PROVIDING ONE OR MORE PHASE VOLTAGES FROM INPUT VOLTAGES


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# CIRCUIT, METHOD AND SYSTEM FOR PROVIDING ONE OR MORE PHASE VOLTAGES FROM INPUT VOLTAGES

## TECHNICAL FIELD OF THE INVENTION

[0001] The present invention is directed, in general, to power circuits and, more specifically, to a circuit, method and system for providing one or more phase voltages from input voltage lines not having a neutral line.

## BACKGROUND OF THE INVENTION

[0002] In a three phase alternating current (AC) system, knowledge of the phase voltages is often required for various control purposes. Because a neutral line is rarely available, the phase voltage is often defined with respect to a virtual neutral point. This virtual neutral point is usually established as the intersection of three equal impedances coupled to respective ones of the voltage lines.

[0003] In practice, inverting operational amplifiers ("opamps") may be employed to provide an estimate of a scaled value of each phase voltage. The positive input of each of the opamps is referenced to a signal (isolated) ground. In power converters, this signal ground is often the converter ground bus.

Unfortunately, a common mode voltage can develop between the virtual neutral point and the signal ground. This common mode voltage can grow to the point that one or more of the opamps fails to indicate accurate line voltages.

**[0004]** The common mode voltage may be reduced by placing an impedance between the virtual neutral point and the signal ground. However, this distorts the virtual neutral point, and the outputs of the inverting amplifiers may no longer accurately reflect the phase voltages.

**[0005]** To resolve a large common mode voltage swing in a switching environment, an isolation transformer or an opto-coupler may be employed with the opamps. The transformer can provide excellent isolation and good linearity, but often its size is a problem as requirements for power converters dictate smaller footprints and higher power density. While opto-couplers provide smaller size, the non-linearity inherent in opto-couplers degrades the accuracy of the voltage measurement. Furthermore, the added isolation may require an isolated bias supply for the power converter, posing additional cost or surface area requirements. Other solutions may work well for a symmetric or balanced voltage condition. However, these solutions usually do not accommodate line voltages that are asymmetric or unbalanced, which is more often the case in real-world environments.

**[0006]** Accordingly, what is needed in the art is an improved way to provide phase voltages from voltage lines that lack a neutral line and that accommodates voltage imbalances.

## SUMMARY OF THE INVENTION

[0007] To address the above-discussed deficiencies of the prior art, the present invention provides a phase voltage circuit. In one embodiment, the phase voltage circuit includes a line voltage stage coupled to at least three input voltage lines and configured to provide at least two corresponding line voltages. The phase voltage circuit also includes a difference voltage stage coupled to the line voltage stage and configured to provide at least one phase voltage from the at least two corresponding line voltages.

[0008] In another aspect, the present invention provides a method of providing at least one phase voltage. The method includes initially providing at least two corresponding line voltages from at least three input voltage lines and subsequently providing the at least one phase voltage from the at least two corresponding line voltages.

[0009] The present invention also provides, in yet another aspect, a phase voltage system for measuring three-phase voltages. The phase voltage system includes three input voltage lines and a phase voltage circuit. The phase voltage circuit has a line voltage stage, coupled to the three input voltage lines, that provides three corresponding line voltages. The phase voltage circuit also has a difference voltage stage, coupled to the line

voltage stage, that provides three corresponding phase voltages from the three corresponding line voltages.

**[0010]** The foregoing has outlined preferred and alternative features of the present invention so that those skilled in the art may better understand the detailed description of the invention that follows. Additional features of the invention will be described hereinafter that form the subject of the claims of the invention. Those skilled in the art should appreciate that they can readily use the disclosed conception and specific embodiment as a basis for designing or modifying other structures for carrying out the same purposes of the present invention. Those skilled in the art should also realize that such equivalent constructions do not depart from the spirit and scope of the invention.

## BRIEF DESCRIPTION OF THE DRAWINGS

**[0011]** For a more complete understanding of the present invention, reference is now made to the following descriptions taken in conjunction with the accompanying drawings, in which:

**[0012]** FIGURE 1 illustrates a system diagram of an embodiment of a three-phase voltage system constructed in accordance with the principles of the present invention;

**[0013]** FIGURE 2 illustrates a vector diagram showing exemplary line and phase voltage relationships that may be employed by the three-phase voltage system of FIGURE 1;

**[0014]** FIGURE 3 illustrates a circuit diagram of an embodiment of a phase voltage circuit constructed in accordance with the principles of the present invention;

**[0015]** FIGURE 4 illustrates a circuit diagram of an embodiment of a three-phase voltage system constructed in accordance with the principles of the present invention;

**[0016]** FIGURE 5 illustrates representative waveforms for a symmetric AC condition associated with a three-phase voltage system constructed in accordance with the principles of the present invention; and

**[0017]** FIGURE 6 illustrates representative waveforms for an asymmetric AC condition associated with a three-phase voltage

system constructed in accordance with the principles of the present invention.

## DETAILED DESCRIPTION

**[0018]** Referring initially to FIGURE 1, illustrated is a system diagram of an embodiment of a three-phase voltage system, generally designated 100, constructed in accordance with the principles of the present invention. The three-phase voltage system 100 includes first, second and third input voltage lines a, b, c and a phase voltage circuit 105. The phase voltage circuit 105 includes a line voltage stage 110 and a difference voltage stage 115. The three input voltage lines a, b, c are without a neutral line.

**[0019]** The line voltage stage 110 is coupled to the first, second and third input voltage lines a, b, c and provides first, second and third line voltages **Vab, Vbc, Vca**. These three line voltages **Vab, Vbc, Vca** correspond to voltages measured between the first and second input voltage lines a, b, the second and third input voltage lines b, c and the third and first input voltage lines c, a, respectively. Additionally, the difference voltage stage 115 is coupled to the three line voltages **Vab, Vbc, Vca** and provides first, second and third phase voltages **Va, Vb, Vc**. The three phase voltages **Va, Vb, Vc** correspond to voltages that exist between a virtual neutral point and the three input voltage lines a, b, c, respectively.

**[0020]** The three-phase voltage system 100 may employ an implementation that utilizes hardware tailored to a specific

application. Alternatively, an implementation may be employed using software that runs on a general purpose device such as a digital signal processor. Of course, an implementation may employ a combination of software and tailored hardware as appropriate to a particular application.

**[0021]** Turning now to FIGURE 2, illustrated is a vector diagram, generally designated 200, showing exemplary line and phase voltage relationships that may be employed by the three-phase voltage system 100 of FIGURE 1. The vector diagram 200 includes an exemplary vector representation 205 relating to first, second and third line voltage vectors **Vab**, **Vbc**, **Vca** and first, second and third phase voltage vectors **Va**, **Vb**, **Vc**, emanating from a virtual neutral point N. The neutral point N resides in the center of a triangle formed by the three line voltage vectors **Vab**, **Vbc**, **Vca** when these voltages are equal in magnitude (indicating a symmetric, or balanced, AC line condition) and is off-center when these voltages are not equal in magnitude (indicating an asymmetric, or unbalanced, AC line condition).

**[0022]** As seen in an exemplary vector representation 205 of the vector diagram 200, the relationship between the line voltages and phase voltages may be expressed by:

$$\mathbf{Vab} = \mathbf{Va} - \mathbf{Vb}, \tag{1a}$$

$$\mathbf{Vbc} = \mathbf{Vb} - \mathbf{Vc}, \text{ and} \tag{1b}$$

$$\mathbf{Vca} = \mathbf{Vc} - \mathbf{Va}. \tag{1c}$$

Then, for a three-phase voltage system without a neutral connection:

$$\mathbf{Vab} - \mathbf{Vca} = (\mathbf{Va} - \mathbf{Vb}) - (\mathbf{Vc} - \mathbf{Va}),$$

$$= 3\mathbf{Va} - (\mathbf{Va} + \mathbf{Vb} + \mathbf{Vc}),$$

$$\mathbf{Vab} - \mathbf{Vca} = 3\mathbf{Va}, \tag{2}$$

since $\mathbf{Va} + \mathbf{Vb} + \mathbf{Vc}$ should equal zero for a three-phase system not having a neutral line. Similarly, it may be shown that the following relationships are generally true for both balanced and unbalanced AC line conditions:

$$\mathbf{Va} = (\mathbf{Vab} - \mathbf{Vca})/3, \qquad (3a)$$

$$\mathbf{Vb} = (\mathbf{Vbc} - \mathbf{Vab})/3, \text{ and} \qquad (3b)$$

$$\mathbf{Vc} = (\mathbf{Vca} - \mathbf{Vbc})/3, \qquad (3a)$$

It is readily seen that dividing the difference in line voltages by a scaling factor of three allows an exact equivalence between a phase voltage and its associated line voltages. The vector diagram 200 also includes an exemplary vector representation 210 illustrating equation (3a).

**[0023]** Turning now to FIGURE 3, illustrated is a circuit diagram of an embodiment of a phase voltage circuit, generally designated 300, constructed in accordance with the principles of the present invention. The phase voltage circuit 300 includes a line voltage stage 305 and a difference voltage stage 310 and provides a phase voltage **Va**. The line voltage stage 305 is coupled to first, second and third input voltage lines a, b, c (which lack a neutral line).

The first, second and third input voltage lines a, b, c provide first, second and third input voltages **Vina, Vinb, Vinc,** respectively. The three input voltages **Vina, Vinb, Vinc** are referenced to a common ground that forms a reference point within the phase voltage circuit 300. The line voltage stage 305 includes first and second line voltage differential amplifiers 306, 307 that provide first and second line voltages **Vab, Vca**, respectively. The difference voltage stage 310 includes a phase voltage differential amplifier 311 coupled to the first and second line voltage differential amplifiers 306, 307.

**[0024]** Each of the first and second line voltage differential amplifiers 306, 307 includes two sets of first and second resistors R1, R2 and an operational amplifier A1 having inverting and non-inverting inputs. The first line voltage differential amplifier 306 provides the first line voltage **Vab** by subtracting the second input voltage **Vinb** from the first input voltage Vina. Similarly, the second line voltage differential amplifier 307 provides the second line voltage **Vca** by subtracting the first input voltage **Vina** from the third input voltage **Vinc**. The first and second line voltage differential amplifiers 306, 307 employ first and second resistors R1, R2 to determine a line voltage scaling factor R1/R2. This line voltage scaling factor R1/R2 may be employed to scale the output levels of the first and second line voltages **Vab, Vca**, as appropriate to a particular application.

**[0025]** The phase voltage differential amplifier 311 include two sets of third and fourth resistors R3, R4 and an operational amplifier A2 having inverting and non-inverting inputs. The phase voltage differential amplifier 311 provides the phase voltage **Va** by subtracting the second line voltage **Vca** from the first line voltage **Vab** to yield a difference. The phase voltage differential amplifier 311 employs the third and fourth resistors R3, R4 to determine a phase voltage scaling factor R3/R4. This phase voltage scaling factor R3/R4 may be employed to scale (for example, divide) the difference between the first line voltage **Vab** and the second line voltage **Vca** as appropriate to the particular application. Therefore, the phase voltage circuit 300 provides a scalable realization of equation (3a) and may be employed for both balanced and unbalanced AC line conditions.

**[0026]** Turning now to FIGURE 4, illustrated is a circuit diagram of an embodiment of a three-phase voltage system, generally designated 400, constructed in accordance with the principles of the present invention. The three-phase voltage system 400 may be employed as an implementation of the three-phase voltage system 100 introduced in FIGURE 1. The three-phase voltage system 400, provides outputs of first, second and third phase voltages **Va, Vb, Vc** and includes three input voltage lines a, b, c that do not employ a neutral line, a line voltage stage 405 and a difference voltage stage 410. The line voltage stage 405 includes first,

second and third line voltage differential amplifiers 406, 407, 408, that provide first, second and third line voltages **Vab, Vbc, Vca,** respectively. The difference voltage stage 410 includes first, second and third phase voltage differential amplifiers 411, 412, 413, that provide the first, second and third phase voltages **Va, Vb, Vc,** respectively.

**[0027]** Each of the first, second and third line voltage differential amplifiers 406, 407, 408 includes two sets of first and second resistors R1, R2 and an operational amplifier A1 having inverting and non-inverting inputs. The first line voltage differential amplifier 406 provides the first line voltages **Vab** by subtracting a second input voltage **Vinb** from a first input voltage **Vina**. The second line voltage differential amplifier 407 provides the second line voltage **Vbc** by subtracting a third input voltage **Vinc** from the second input voltage **Vinb**. And, the third line voltage differential amplifier 408 provides the third line voltage **Vbc** by subtracting the first input voltage **Vina** from the third input voltage **Vinc**. A line voltage scaling factor R1/R2 may be employed to scale these differences in input voltages as appropriate to an application.

**[0028]** Each of the first, second and third phase voltage differential amplifiers 411, 412, 413 includes two sets of third and fourth resistors R3, R4 and an operational amplifier A2 having

inverting and non-inverting inputs. The first phase voltage differential amplifier 411 provides the first phase voltage **Va** by subtracting the third line voltage **Vca** from the first line voltage **Vab**. The second phase voltage differential amplifier 412 provides the second phase voltage **Vb** by subtracting the first line voltage **Vab** from the second line voltage **Vbc**. And, the third phase voltage differential amplifier 413 provides the third phase voltage **Vc** by subtracting the second line voltage **Vbc** from the third line voltage **Vca**. A phase voltage scaling factor R3/R4 may be employed to divide these line voltage differences as appropriate to an application. Of course, an overall scaling factor of (R1/R2)*(R3/R4) equal to three provides phase voltage magnitudes that accurately represent the line voltage magnitudes.

**[0029]** Turning now to FIGURE 5, illustrated are representative waveforms for a symmetric AC condition, generally designated 500, associated with a three-phase voltage system constructed in accordance with the principles of the present invention. The representative waveforms 500 include reference phase voltage waveforms 505 and recovered phase voltage waveforms 510. The reference phase voltage waveforms 505 include first, second and third reference phase voltages $\mathbf{Va}_{ref}$, $\mathbf{Vb}_{ref}$, $\mathbf{Vc}_{ref}$ that may be associated with first, second and third voltage lines (such as those discussed with respect to FIGUREs 1 and 4) that do not employ a neutral line. The recovered phase voltage waveforms 510 include

corresponding first, second and third recovered phase voltages **Va, Vb, Vc**, respectively, that represent the phase voltage outputs discussed with respect to FIGUREs 1 and 4. As may be seen in FIGURE 5, the recovered phase voltage waveforms 510 bear a close correlation to the symmetrical reference phase voltage waveforms 505. As also seen, a scaling factor has been applied to the recovered phase voltage waveforms 510, thereby allowing a requirement associated with their application to be met.

**[0030]** Turning now to FIGURE 6, illustrated are representative waveforms for an asymmetric AC condition, generally designated 600, associated with a three-phase voltage system constructed in accordance with the principles of the present invention. The representative waveforms 600 include reference phase voltage waveforms 605 and corresponding recovered phase voltage waveforms 610. The reference phase voltage waveforms 605 include first, second and third reference phase voltages $\mathbf{Va}_{ref}$, $\mathbf{Vb}_{ref}$, $\mathbf{Vc}_{ref}$ that employ differing amplitudes and may be associated with first, second and third voltage lines that do not employ a neutral line, as discussed before. The recovered phase voltage waveforms 610 include corresponding respective first, second and third recovered phase voltages **Va, Vb, Vc**. Again, as may be seen in FIGURE 6, the scaled and recovered phase voltage waveforms 610 closely correlate in phase and relative amplitude with the asymmetrical reference phase voltage waveforms 605.

[0031] In summary, embodiments of the present invention directed to a phase voltage circuit, a method of providing at least one phase voltage and a phase voltage system employing a plurality of phase voltages have been presented. Advantages include the ability to recover associated phase voltages from voltage lines that do not employ a neutral line, even under asymmetric AC conditions. Additionally, the recovered phase voltages may be scaled by a factor equaling the number of phases to provide an accurate phase voltage representation of the associated input voltage lines.

[0032] Although the present invention has been described in detail, those skilled in the art should understand that they can make various changes, substitutions and alterations herein without departing from the spirit and scope of the invention in its broadest form.